Thermal Conductivity of Mixed Refrigerants

R404A, R407C, R410A, and R507A [1]

V. Z. Geller,[2,4] B. V. Nemzer,[2] and U. V. Cheremnykh [3]

---

[1] Paper presented at the Fourteenth Symposium on Thermophysical Properties, June 25–30, 2000, Boulder, Colorado, U.S.A.

[2] Thermophysics Research Center, 2278 20th Avenue, San Francisco, CA, U.S.A.

[3] Odessa State Academy of Refrigeration, 1/3 Dvoryanskaya St., Odessa, 270026, Ukraine.

[4] To whom correspondence should be addressed.

ABSTRACT

New thermal conductivity data of the mixed refrigerants R404A, R407C, R410A, and R507C are presented. For all these refrigerants, the thermal conductivity was measured in the vapor phase at atmospheric pressure over a temperature range from 250 to 400 K and also at moderate pressures. A modified steady-state hot-wire method has been used for these measurements. The cumulative correction for end effects, eccentricity of the wire, and radiation heat transfer did not exceed 2%. Calculated uncertainties in experimental thermal conductivity are, in general, less than or equal to $\pm$1%. All available literature thermal conductivity data for R404A, R407C, R410A, and R507C were evaluated to identify the most accurate data on which to base the thermal conductivity model. The thermal conductivity is modeled with the residual concept. In this representation, the thermal conductivity was composed of two contributions: a dilute gas term which is a function only of temperature, and a residual term which is a function only of density. The models cover a wide range of parameters except for the region of the critical thermal conductivity enhancement. The resulting correlations applicable for the thermal conductivity of dilute gas, superheated vapor, and saturated liquid and vapor far away from the critical point are given. Comparisons are made for all available literature data.

KEY WORDS: hot-wire method, measurements, model, refrigerants, R404A, R407C, R410A, R507A, thermal conductivity, vapor phase.

1. INTRODUCTION

Mixed refrigerants R404A (R125/R134a/143a, 44/4/52 wt %), R407C (R32/R125/R134a, 23/25/52 wt %), R410A (R32/R125, 50/50 wt %), and R507A (R125/R143a, 50/50 wt %) are recommended as a replacement for R22 and R502. Accurate thermal conductivity data for these refrigerants are needed for the design of refrigeration equipment using refrigerant blends; the thermal conductivity is particularly important for the design of the condenser and evaporator. Available literature viscosity data for these fluids are limited and do not cover a range of parameters required for the engineering applications (saturated-liquid and saturated-vapor thermal conductivity and thermal conductivity for the superheated vapors). There are only a few sources of thermal conductivity data of R404A, R407C, R410A, and R507A. For R404A, the saturated liquid thermal conductivity was measured by steady-state hot-wire method over a temperature range from 253 to 334 K with the estimated uncertainty $\pm$1% [1]. Hoffmann, Spindler, Hahne, and Sohns [2, 3] measured the thermal conductivity of liquid R407C, R410A, and R507A along the suturated line over a temperature range from 257 to 328 K using a transient hot-wire method. The estimated uncertainty of these data are $\pm$2%. They have also mentioned the measurements of the saturated vapor thermal conducivity, however the experimental results were not reported. Ro, Kim, and Jeong [4, 5] have measured the liquid thermal conductivity of R407C and R410A over a temperature range from 233 to 323 K and a pressure range from 2 to 20 MPa. They used a transient hot-wire method with the estimated uncertainties $\pm$2%. Gao, Nomura, Nagasaka, and Nagashima [6,7] have published the measurements of the liquid thermal conductivity of R407C and R410A over a temperature range from 193 to 293 K and from 213 to 293 K, respectively, and a pressure range from 2 to 30 MPa with the estimated uncertainty of $\pm$0.7%.

A single set of data is available for vapor thermal conductivity (R410A). Tanaka, Matsuo, and Taya have measured the thermal conductivity of R32/R125 mixtures in the vapor phase at the isothers 283.15 K and 298.15 K over a pressure range from 0.1 to 1.1 MPa and a range of a mole fraction of R32 from 0.19 to 0.82 [8]. Thermal conductivity data of R410A found by interpolation of these results cover a range of reduced density from 0.01 to 0.08.

In this paper, we present new thermal conductivity measurements of R404A, R407C, R410A, and R507A covering a part of the "blank spaces" in the thermal conductivity - density diagram outside the critical region and including vapor thermal conductivity at atmospheric pressure and superheated vapor thermal conductivity.

2. MEASUREMENTS

Thermal conductivity were measured using a modified steady-state hot-wire method. A detailed description of the apparatus and the experimental technique are given elsewhere [1]. A special feature of this apparatus is the application of a thin-walled platinum capillary tube (outside diameter = 1.0 mm, inside diameter = 0.9 mm) as the outer resistance thermometer. A platinum wire (diameter = 0.1 mm and length = 80 mm) located inside this capillary tube is used as an electric heater and at the same time as the inner resistance thermometer. In order to center this wire inside the capillary tube, the latter was placed within a glass tube that can be adjusted in two orthogonal directions by set screws. The wire was centered by visual observation using a microscope. The frame for this apparatus was designed to have minimal clearance with the glass tube, thus eliminating convection heat transfer on the outside of the tube.

The thermal conductivity measuring cell was installed in a high-pressure vessel placed in a special constant temperature bath to provide temperature control to within $\pm$0.002 K. The temperatures of both resistance thermometers were determined by measuring the potential difference across each thermometer relative to the potential across standard resistances. The accuracy of these measurements using a digital voltmeter is to within $\pm$1 nV. The pressure was measured with a digital pressure transducer to within $\pm$1 kPa. During the thermal conductivity measurements the temperature difference in the fluid sample between the wire and the capillary tube is 2 - 10 K. For these conditions, $Ra = Gr \cdot Pr$ numbers were less than 500 in all experiments, indicating negligible effects due to natural convection.

Thermal conductivity were calculated taking into account corrections for end effects, eccentricity of the wire, and radiation heat transfer. The cumulative correction did not exceed 2% of the measured thermal conductivity values. Calculated uncertainties in the experimental thermal conductivity are less than or equal to $\pm$1%.

3. RESULTS

Experiments for the thermal conductivity of R404A, R407C, R410A, and R507A at atmospheric pressure were carried out over a temperature range from 250 to 400 K. For the superheated vapor, the experiments were performed at four isotherms. In these experiments, the highest pressure was lower than the saturated vapor pressure by approximately 0.05-0.1

MPa. The density and vapor pressure for all mixed refrigerants were calculated using REFPROP, Version 6.01 [9].

The obtained results are given in Tables. I-IV.

4. MODEL AND CORRELATIONS

The most known models for the thermal conductivity calculations use the form of the sum of three contributions

$$l\,(r,\,T) = \ l_0\,(T) + D\,l\,(r,\,T) + D_c\,l\,(r,\,T) \tag{1}$$

where l is the thermal conductivity, l_0 is the thermal conductivity in the zero-density limit, $D\,l = \ l - \ l_0$ is the residual thermal conductivity, $D_c\,l$ is the critical thermal conductivity enhancement, T is the temperature, r is the density. Each contribution may be treated independently by using both theoretical and available experimental information.

The residual thermal conductivity as a function of both density and temperature describes thermal conductivity data over a wide range of parameters including high density region (liquid at very low temperatures, compressed liquid). For available thermal conductivity data of R404A, R407C, R410A, and R507A, the residual thermal conductivity as a function only of density provides good agreement between the experimental and calculated results.

The critical enhancement is significant for the thermal conductivity in the critical region, however, this information is currently unavailable for the refrigerants under consideration. Thus, in this representation, the thermal conductivity was composed of two contributions: a dilute gas term which is a function only of temperature, and a residual term which is a function only of density:

$$l_0 = a_1 T + a_2 T^2 \tag{2}$$

$$D\,l = b_1 r_r + b_2 r_r^{\,2} + b_3 r_r^{\,3} + b_4 r_r^{\,4} \tag{3}$$

where T is in K, $r_r = r/r_c$ is the reduced density. The coefficients a_i and b_j , and also the values of the critical density r_c taken for these calculations are given in Table V.

Comparisons were made for the calculated thermal conductivity with the available published experimental results [1-8] and also with the data of present work. The deviations $(l_{exp} - l_{calc})/l_{calc} \cdot 100\%$ are shown in Fig. 1 for liquid R404A and R407C and in Fig. 2 for liquid R410A and R507A. Fig. 3 shows comparisons of the calculated and experimental thermal conductivity data for R404A, R407C, R410A, and R507A in the vapor phase. The agreement between the experimental data and the calculated thermal conductivity is quite satisfactory: the deviations, in general, do not exceed $\pm$3.5% in the liquid phase (except for a few experimental points for R410A) and $\pm$2.3% in the vapor phase.

5. CONCLUSIONS

New thermal conductivity measurements for mixed refrigerants R404A, R407C, R410A, and R507A in the vapor phase are presented. Thermal conductivity was measured using a modified steady-state hot-wire method with uncertainties $\pm$1%. The thermal conductivity is modeled with the residual concept where a residual term is a function only of density. The model covers a wide range of parameters outside the critical region. The resulting thermal conductivity correlations are given and comparisons are made for all available literature data.

REFERENCES

1. V. Z. Geller, M. E. Paulaitis, D. B. Bivens, A. Yokozeki, in *Proc. ASHRAE /NIST Refrigerants Conf.*, (Gaithersburg, MD, 1993), p. 73.

2. N. Hoffmann, K. Spindler, E Hahne, *Bestimmung der Transportgroessen von HFKW, Heft 2, Waermeleitfaehigkeit.* Forschungsrat Kaeltetechnik E.V., (Frankfurt, 1996).

3. K. Spindler, N. Hoffman, J. Sohns, E. Hahne, *High Temp.-High Press.*, **29**:659 (1997).

4. S. T. Ro, M. S. Kim, S. U. Jeong, *Int. J. Thermophysics*, **18**:991 (1997).

5. S. U. Jeong, M. S. Kim, S. T. Ro, in *Proc. of 5th Asian Thermophys. Prop. Conf.* (Seoul, Korea, 1998), p. 423.

6. X. Gao, K. Nomura, Y. Nagasaka, A. Nagashima, *High Temp.-High Press.*, **29**:39 (1997).

7. X. Gao, Y. Nagasaka, A. Nagashima, *Int. J. Thermophysics*, **20**: 5 (1999).

8. Y. Tanaka, S. Matsuo, S. Taya, *Int. J. Thermophysics*, **16**:121 (1995).

9. M. O. McLinden, S. A. Klein, E. W. Lemmon, A. P. Peskin, NIST Thermodymic and Transport Properties of Refrigerants and Refrigerant Mixtures-REFPROP, Version 6.01 (NIST, Gaithersburg, MD, 1988).

Table I. Experimental Thermal Conductivity Data of R404A

Temperature (K)	Pressure (MPa)	Thermal conductivity ($mW \cdot m^{-1} \cdot K^{-1}$)	Temperature (K)	Pressure (MPa)	Thermal conductivity ($mW \cdot m^{-1} \cdot K^{-1}$)
252.80	0.101	9.90	313.29	0.833	15.55
253.03	0.101	9.91	313.40	0.836	15.62
273.26	0.101	11.51	313.33	1.234	16.38
273.38	0.102	11.54	313.46	1.235	16.43
273.29	0.534	12.28	313.39	1.466	16.90
273.50	0.538	12.39	313.49	1.466	16.96
293.16	0.102	12.98	313.34	1.762	17.92
293.27	0.102	13.10	313.45	1.763	17.98
293.20	0.310	13.44	334.25	0.101	16.02
293.31	0.311	13.46	334.33	0.101	16.04
293.22	0.688	14.12	334.23	0.677	16.72
293.31	0.690	14.16	334.30	0.679	16.75
293.19	0.944	14.67	334.23	0.922	17.11
293.26	0.945	14.78	334.31	0.924	17.13
313.37	0.101	14.44	334.26	1.345	17.73
313.51	0.101	14.47	334.36	1.347	17.75
313.38	0.455	14.96	334.28	1.688	18.52
313.53	0.458	15.10	334.34	1.689	18.55

Table I. Experimental Thermal Conductivity Data of R04A (Cont'd)

Temperature (K)	Pressure (MPa)	Thermal conductivity ($mW \cdot m^{-1} \cdot K^{-1}$)	Temperature (K)	Pressure (MPa)	Thermal conductivity ($mW \cdot m^{-1} \cdot K^{-1}$)
334.27	2.173	19.91	334.36	2.763	22.34
334.38	2.176	19.93	365.48	0.101	18.27
334.27	2.450	20.74	365.54	0.101	18.31
334.47	2.450	20.78	393.02	0.101	20.26
334.25	2.762	22.29	393.09	0.101	20.22

Table II. Experimental Thermal Conductivity Data of R407C

Temperature (K)	Pressure (MPa)	Thermal conductivity ($mW \cdot m^{-1} \cdot K^{-1}$)	Temperature (K)	Pressure (MPa)	Thermal conductivity ($mW \cdot m^{-1} \cdot K^{-1}$)
253.27	0.101	9.68	314.41	1.235	15.91
253.45	0.101	9.70	314.30	1.512	16.63
272.13	0.101	11.15	314.42	1.513	16.63
272.22	0.101	11.17	333.22	0.101	15.82
272.17	0.387	11.67	333.29	0.102	15.82
272.28	0.388	11.66	333.24	0.556	16.24
293.00	0.101	12.76	333.31	0.558	16.27
293.11	0.101	12.79	333.23	0.987	16.80
293.02	0.434	13.28	333.35	0.989	16.76
293.13	0.435	13.32	333.20	1.446	17.28
293.00	0.822	13.77	333.31	1.446	17.34
293.15	0.823	13.81	333.20	1.880	18.22
314.26	0.101	14.40	333.33	1.882	18.31
314.38	0.101	14.44	333.21	2.447	19.88
314.25	0.456	14.88	333.30	2.448	19.91
314.39	0.458	14.87	363.05	0.101	18.11
314.28	0.877	15.41	363.13	0.101	18.14
314.42	0.879	15.44	389.70	0.101	20.12
314.27	1.234	15.93	389.83	0.101	20.09

Table III. Experimental Thermal Conductivity Data of R410A

Temperature (K)	Pressure (MPa)	Thermal conductivity ($mW \cdot m^{-1} \cdot K^{-1}$)	Temperature (K)	Pressure (MPa)	Thermal conductivity ($mW \cdot m^{-1} \cdot K^{-1}$)
255.04	0.101	9.98	314.21	0.512	14.86
260.32	0.101	10.43	314.37	0.513	14.89
274.02	0.101	11.43	314.22	1.011	15.58
274.16	0.101	11.44	314.34	1.012	15.62
274.04	0.377	11.75	314.23	1.632	16.56
274.12	0.378	11.80	314.36	1.633	16.61
274.08	0.712	12.35	314.25	2.012	17.09
274.17	0.713	12.34	314.43	2.012	17.16
294.26	0.101	12.92	314.19	2.353	18.03
294.32	0.101	12.94	314.35	2.354	18.22
294.30	0.507	13.49	331.97	0.101	15.73
294.38	0.507	13.53	332.05	0.102	15.73
294.25	0.944	14.15	332.00	0.622	16.28
294.39	0.946	14.18	332.10	0.625	16.27
294.26	1.376	14.92	332.01	1.102	16.74
294.41	1.377	15.01	332.10	1.104	16.75
314.17	0.101	14.40	331.96	1.722	17.78
314.30	0.101	14.41	332.07	1.724	17.68

Table III. Experimental Thermal Conductivity Data of R410A (Cont'd)

Temperature (K)	Pressure (MPa)	Thermal conductivity ($mW \cdot m^{-1} \cdot K^{-1}$)	Temperature (K)	Pressure (MPa)	Thermal conductivity ($mW \cdot m^{-1} \cdot K^{-1}$)
331.95	2.345	18.50	332.09	3.690	22.76
332.06	2.347	18.51	346.17	0.101	16.85
331.99	3.004	19.98	349.37	0.101	17.08
332.12	3.007	20.06	384.03	0.101	19.56
332.00	3.325	20.85	387.25	0.101	19.78
332.13	3.327	20.84	404.52	0.101	21.04
332.01	3.688	22.69	409.81	0.101	21.52

Table IV. Experimental Thermal Conductivity Data of R507A

Temperature (K)	Pressure (MPa)	Thermal conductivity ($mW \cdot m^{-1} \cdot K^{-1}$)	Temperature (K)	Pressure (MPa)	Thermal conductivity ($mW \cdot m^{-1} \cdot K^{-1}$)
254.71	0.101	10.09	314.40	1.124	16.13
254.85	0.101	10.07	314.26	1.733	17.56
274.03	0.101	11.58	314.39	1.735	17.64
274.16	0.101	11.61	333.22	0.101	15.97
274.04	0.533	12.30	333.36	0.101	15.98
274.16	0.534	12.36	333.20	0.478	16.49
293.82	0.101	13.10	333.31	0.477	16.54
293.94	0.102	13.12	333.22	0.933	17.13
293.85	0.666	13.77	333.30	0.934	17.08
293.97	0.667	13.82	333.23	1.655	18.31
293.80	1.034	14.66	333.35	1.658	18.36
293.88	1.035	14.69	333.21	2.145	19.47
314.29	0.101	14.58	333.34	2.145	19.48
314.43	0.101	14.56	333.18	2.644	21.31
314.27	0.478	14.99	333.28	2.647	21.38
314.40	0.478	15.05	372.03	0.101	18.77
314.28	1.123	16.00	372.17	0.101	18.76

Table V. Coefficients of Equations (2) and (3) and critical densities

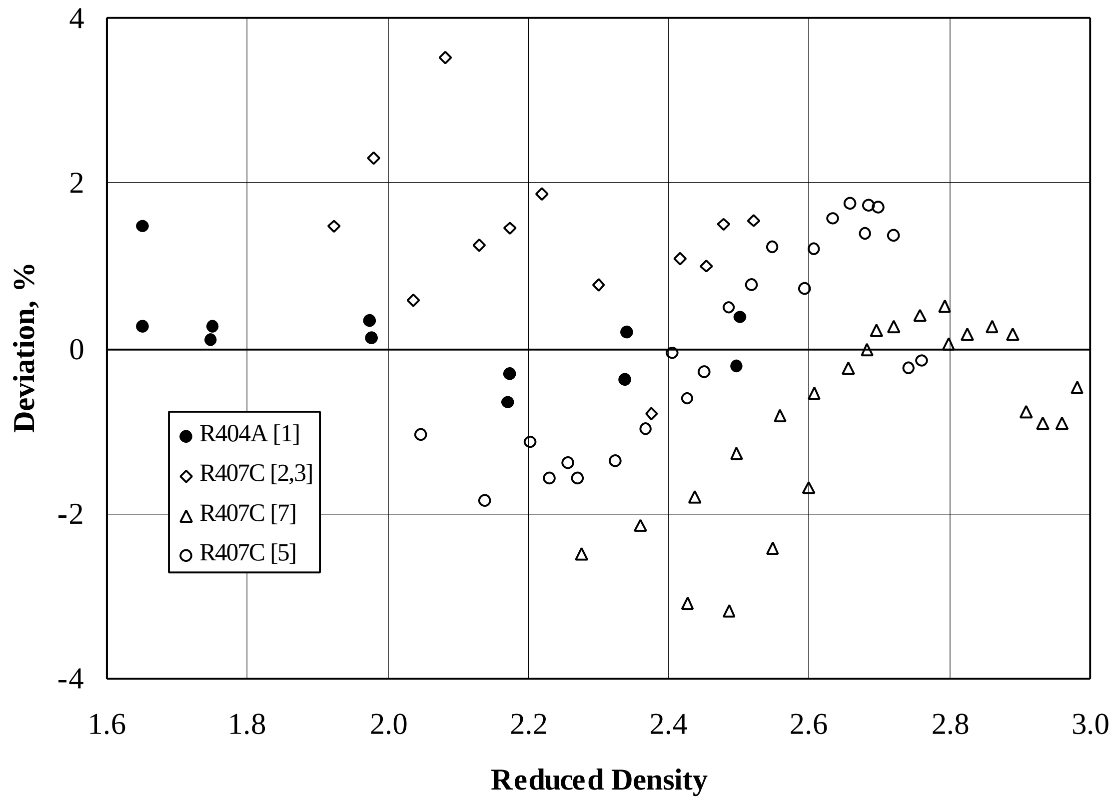
	R404A	R407C	R410A	R507A
a_0	-8.624	-9.628	-8.872	-8.656
a_1	$7.360\cdot10^{-2}$	$7.638\cdot10^{-2}$	$7.410\cdot10^{-2}$	$7.383\cdot10^{-2}$
b_1	$1.574\cdot10^{1}$	$1.392\cdot10^{1}$	$1.974\cdot10^{1}$	$1.379\cdot10^{1}$
b_2	6.130	$1.304\cdot10^{1}$	-2.755	7.435
b_3	-3.139	-6.620	7.300	-4.356
b_4	1.143	1.992	$-3.437\cdot10^{-1}$	1.535
Critical Density ($kg \cdot m^{-3}$)	488.5	512.7	551.9	492.5

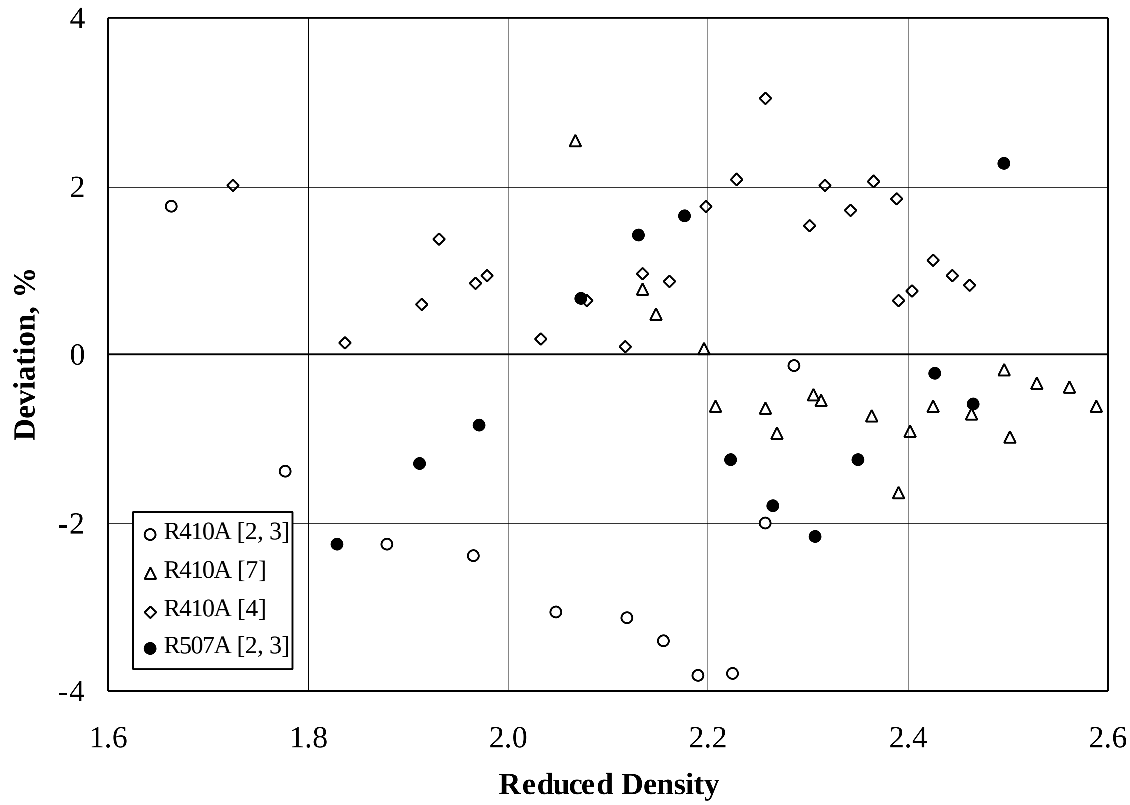
FIGURE CAPTIONS

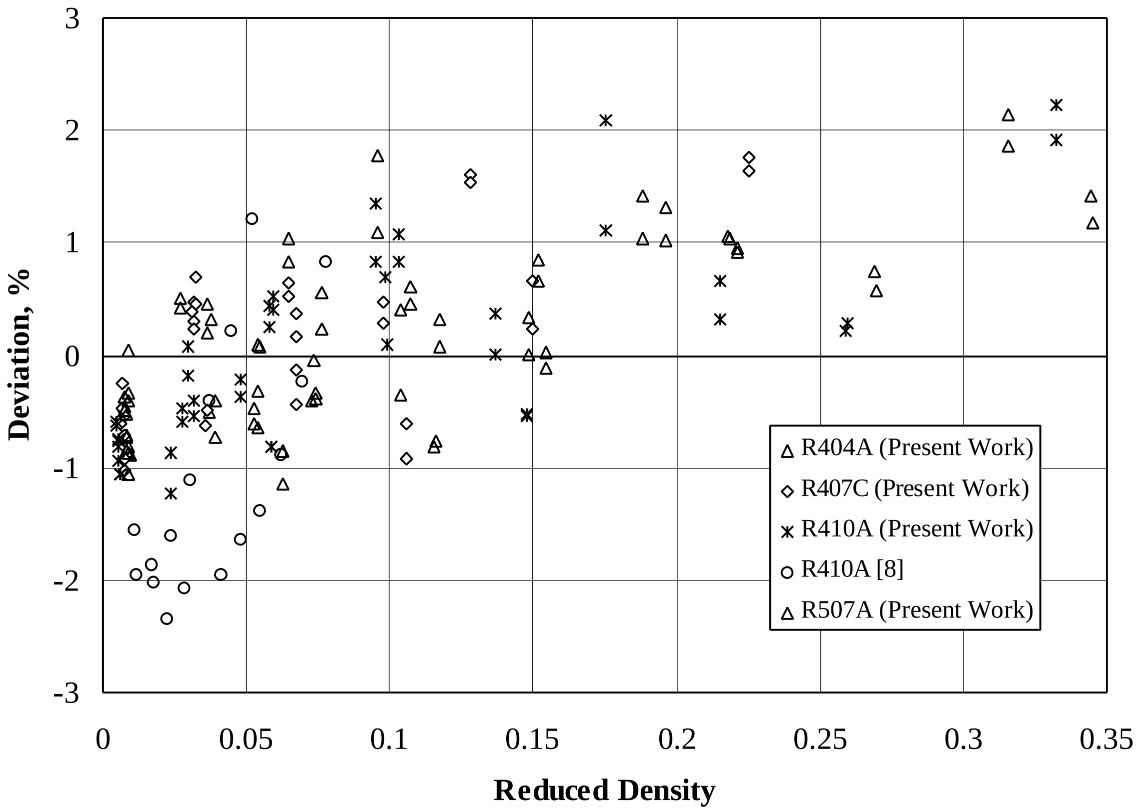
Fig. 1. Deviation of measured thermal conductivity of liquid R404A and R407C from the thermal conductivity calculated by Eqs. (2) and (3) as a function of reduced density

Fig. 2. Deviation of measured thermal conductivity of liquid R410A and R507A from the thermal conductivity calculated by Eqs. (2) and (3) as a function of reduced density

Fig. 3. Deviation of measured vapor thermal conductivity of R404A, R407C, R410A, and R507A from the thermal conductivity calculated by Eqs. (2) and (3) as a function of reduced density


4
2
0
-2
-4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
Deviation, %
Reduced Density
R404A [1]
R407C [2,3]
R407C [7]
R407C [5]


4
2
0
-2
-4
Deviation, %
1.6
1.8
2.0
2.2
2.4
2.6
Reduced Density
R410A [2, 3]
R410A [7]
R410A [4]
R507A [2, 3]


3
2
1
0
-1
-2
-3
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
Deviation, %
Reduced Density
R404A (Present Work)
R407C (Present Work)
R410A (Present Work)
R410A [8]
R507A (Present Work)